

Constraints on dark forces from the B factories and low-energy experiments

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On the behalf of the BABAR Collaboration.

Abstract

The idea that dark-matter interactions with Standard-Model particles may be mediated by new bosons with masses in the MeV-to-GeV range took off several years ago. Constraints on such models were soon calculated based on older measurements. Subsequently, active collaborations conducted dedicated searches for these bosons, and new experiments were planned to improve the search sensitivity. I review the basic models that predict dark vectors and dark Higgs bosons in this mass range, the constraints from electron-positron colliders, fixed-target experiments, and hadron colliders, and comment on the sensitivities of future experiments.

To appear in the proceedings of the Interplay between Particle and Astroparticle Physics workshop, 18 – 22 August, 2014, held at Queen Mary University of London, UK.

1 Dark forces

The colorful term “dark forces” refers to interactions involving dark-matter particles, particularly to the extent that they serve as “portals” between the Standard Model (SM) particles and those of the dark-matter sector (DS). Recently, scenarios in which such interactions are mediated by GeV-scale particles have generated a great deal of interest. Such a model was proposed in Ref. [1] in order to explain chiefly the rise in the cosmic-ray positron fraction with energy, starting around 10 GeV, as seen by PAMELA [2] and later confirmed with high precision by AMS-02 [3]. This rise is also consistent with secondary positron production due to collisions of primary cosmic rays with interstellar gas and dust. However, the idea that it may partly be due to physics beyond the Standard Model has proven almost revolutionary: it has motivated much theoretical and experimental work on new, GeV-scale states, including the construction of new experiments.

We describe here two types of portals. In the vector portal, one postulates the existence of a $U(1)$ gauge interaction in the dark sector, which mixes with the SM $U(1)_Y$. After electroweak symmetry breaking, the effective Lagrangian mixes the associated dark photon A' with the SM photon:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where $F'_{\mu\nu}$ is the dark photon field, ϵ is the effective mixing parameter, and $m_{A'}$ is the dark photon mass, which may be generated by the breaking of a larger symmetry. Phenomenologically, a dark photon may be created in electromagnetic processes, replacing a virtual

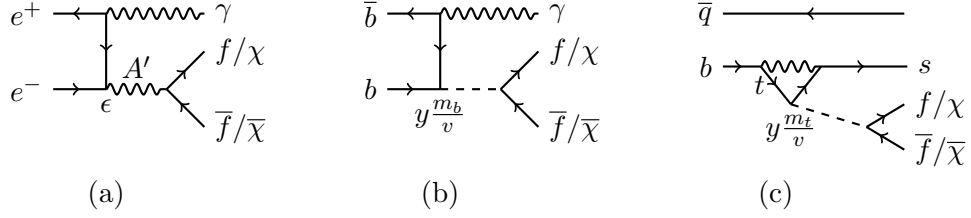


Figure 1: Feynman diagrams for (a) dark-photon production in e^+e^- collisions, (b) dark-Higgs production in Υ decay, and (c) dark-Higgs production in penguin B decay. The dark photon A' or dark Higgs ϕ is shown decaying into a pair of SM fermions $f\bar{f}$ or invisible dark-sector fermions $\chi\bar{\chi}$.

SM photon, and may then decay back into a pair of SM fermions $f\bar{f}$ or dark-sector fermions (WIMPs) $\chi\bar{\chi}$. In e^+e^- collisions, the relevant Feynman diagram is shown in Fig. 1(a).

The Higgs portal features a light scalar ϕ , which mixes slightly with the SM Higgs, and therefore has mass-proportional couplings to the SM fermions. The effective Lagrangian may be written as [4]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - y \frac{m_f}{v} \phi \bar{f} f - \frac{1}{2} \kappa \phi \bar{\chi} \chi, \quad (2)$$

where y is the effective scalar-mixing parameter, and κ is the dark-Higgs coupling to the WIMP. The $\phi \bar{f} f$ term enables creation of the dark Higgs in radiative decays of the narrow $\Upsilon(nS)$ resonances (where $n = 1, 2, 3$), shown in Fig. 1(b). Production in radiative decays of the J/ψ are also interesting, although they are suppressed due to the small charm-quark mass. Another possibility for production of the dark Higgs is in penguin B -meson decays, shown in Fig. 1(c). These have two advantages over Υ decays: the first is that B mesons are many orders of magnitude narrower than the Υ states, and the second is the large coupling of the dark Higgs to the top quark in the penguin loop. On the other hand, penguin B decays have a very small branching fraction compared with radiative Υ decays. Furthermore, production in B decays is limited to dark-Higgs masses of $m_\phi \lesssim 4.5$ GeV.

2 B factories and other dark-forces facilities

Electron-positron B factories are well suited for searching for new physics at the GeV scale, mainly due to their large data samples. Together, *BABAR* [5, 6] and *Belle* [7] have collected about 1.6 fb^{-1} [8] at and around the Υ resonances. This large sample, plus the sizeable $e^+e^- \rightarrow \gamma\gamma$ cross section of about 3 nb at B -factory energies, give an idea of the ϵ sensitivity of these experiments.

Fixed-target experiments typically have much larger integrated luminosities and lower center-of-mass energies than collider experiments. As a result, they are sensitive to lower values of ϵ at lower regions of $m_{A'}$.

The Higgs-portal sensitivity of the B factories stems from their large sample of B mesons, pair-produced in $\Upsilon(4S)$ decays, as well as samples of the narrow $\Upsilon(1S, 2S, 3S)$ resonances.

BABAR has collected $(470.9 \pm 2.8) \times 10^6$ $\Upsilon(4S)$ mesons [9], $(121.8 \pm 1.2) \times 10^6$ $\Upsilon(3S)$ mesons, and $(98.6 \pm 0.9) \times 10^6$ $\Upsilon(2S)$ mesons. The numbers for Belle are 657×10^6 $\Upsilon(4S)$, 3×10^6 $\Upsilon(3S)$, 25×10^6 $\Upsilon(2S)$, and 6×10^6 $\Upsilon(1S)$.

Hadron-collider experiments produce B mesons with a much larger cross section than e^+e^- colliders. However, they typically require muons to trigger on, and are therefore sensitive mostly to $B \rightarrow K\mu^+\mu^-$.

3 Vector-portal constraints

BABAR has searched for a dark photon produced via the diagram in Fig. 1(a), in the final states $A' \rightarrow e^+e^-$ and $\mu^+\mu^-$ [10]. Figs. 2(a) and 2(b) show the invariant-mass distribution of the e^+e^- pairs and the reduced mass $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$, which is better modeled at low values, for $\mu^+\mu^-$ pairs. Several known SM resonances are visible on top of a smooth continuum background from radiative Bhabha scattering and dimuon events. Discrepancies between the data and the Monte Carlo predictions are visible, particularly in the low $m_{e^+e^-}$ region, for which the Monte-Carlo generator is not designed. However, the analysis does not rely on the generator. *BABAR* search for a signal by fitting for a single signal peak, which is moved in small mass steps. In each fit, a mass region at least 20 times wider than the signal resolution is used, and the background shape is taken to be a third- or fourth-order polynomial. The signal yields and significances as functions of mass are shown in Figs. 2(c) and 2(d) for the two modes, respectively.

BABAR did not observe a significant signal, and set 90% confidence-level (CL) upper limits on the dark-photon mixing parameter ϵ vs. its mass $m_{A'}$. These preliminary constraints are labeled “*BABAR* 2014” in Fig. 3. Also shown in Fig. 3 are several other results, which at high mass are less sensitive. These are a reinterpretation of a *BABAR* search for a light Higgs (labeled “*BABAR* 2009”. See Sec. 4) [11]; dark-photon searches by KLOE using $e^+e^- \rightarrow \mu^+\mu^-\gamma$ [12] and $\phi(1020) \rightarrow \eta e^+e^-$ [13]; searches for $A' \rightarrow e^+e^-$ by the electron-nucleus fixed-target experiments APEX [14] and A1 [15]; a $A' \rightarrow e^+e^-$ search by the proton fixed-target experiment HADES [16]; and a search by WASA using $\pi^0 \rightarrow r^+e^-\gamma$ [17]. For small $m_{A'}$ values, limits have been obtained [18] from older electron-beam-dump experiments, of which only constraints from E774 [19] and E141 [20] are shown in Fig. 3, as well as proton-beam-dump experiments and the cooling rate of supernova SN1978A (not shown) [21]. Also shown in Fig. 3 are the constraints from measurement of the electron magnetic moment [22] and the band of favored ϵ vs. $m_{A'}$ values obtained if one attributes to the dark photon the discrepancy between the measured and SM-calculated values of the muon magnetic moment [23]. This favored band is now almost completely excluded by the results shown, as well as by a new $e^+e^- \rightarrow e^+e^-\gamma$ search from KLOE [24], not shown in Fig. 3.

Tighter constraints will be obtained from future measurements. Between them, the DarkLight, APEX, and HPS experiments [25] at Jefferson Lab will be able to exclude ϵ values above about 3×10^{-4} for a broad range of $m_{A'}$ between 10^{-6} eV and 300 MeV. HPS will also search for displaced vertices formed by decays of long-lived dark photons, with sensitivity to ϵ between about 10^{-5} and 10^{-4} in the approximate mass range $30 < m_{A'} <$

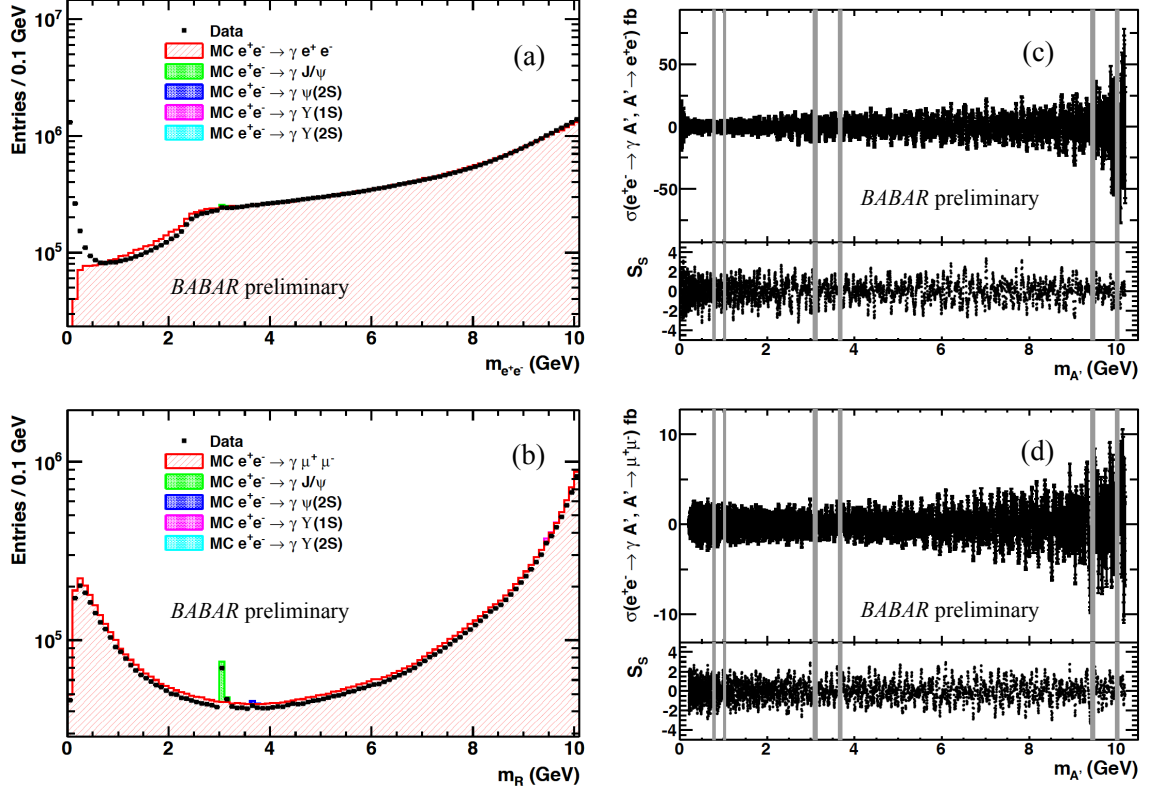


Figure 2: (a) Distributions of the invariant mass for e^+e^- pairs and (b) the reduced mass $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$ for $\mu^+\mu^-$ pairs, and (c,d) the respective signal yields and significances as functions of mass in the *BABAR* dark-photon search [10].

200 MeV. A search by Belle should yield limits similar to those of *BABAR*, given that the analysis is background-dominated, so that the ϵ sensitivity scales as the fourth root of the integrated luminosity. Belle-II, however, will have 100 times more integrated luminosity than *BABAR*, and factors of 2 better trigger efficiency and mass resolution, thus reaching roughly 6-fold tighter limits on ϵ . The predicted sensitivities of these future experiments are also shown in Fig. 3.

BABAR and Belle have also searched for a dark photon in the dark-Higgsstrahlung scenario. In this case, the A' radiates an on-shell dark Higgs, which decays into two on-shell dark vectors. The resulting upper limits from *BABAR* [26] and preliminary limits from Belle [27] are shown in Fig. 4. We note that the final state of three dark photons with the same mass has very little background, so that the limits improve approximately linearly with luminosity, implying a two-orders-of-magnitude improvement at Belle-II.

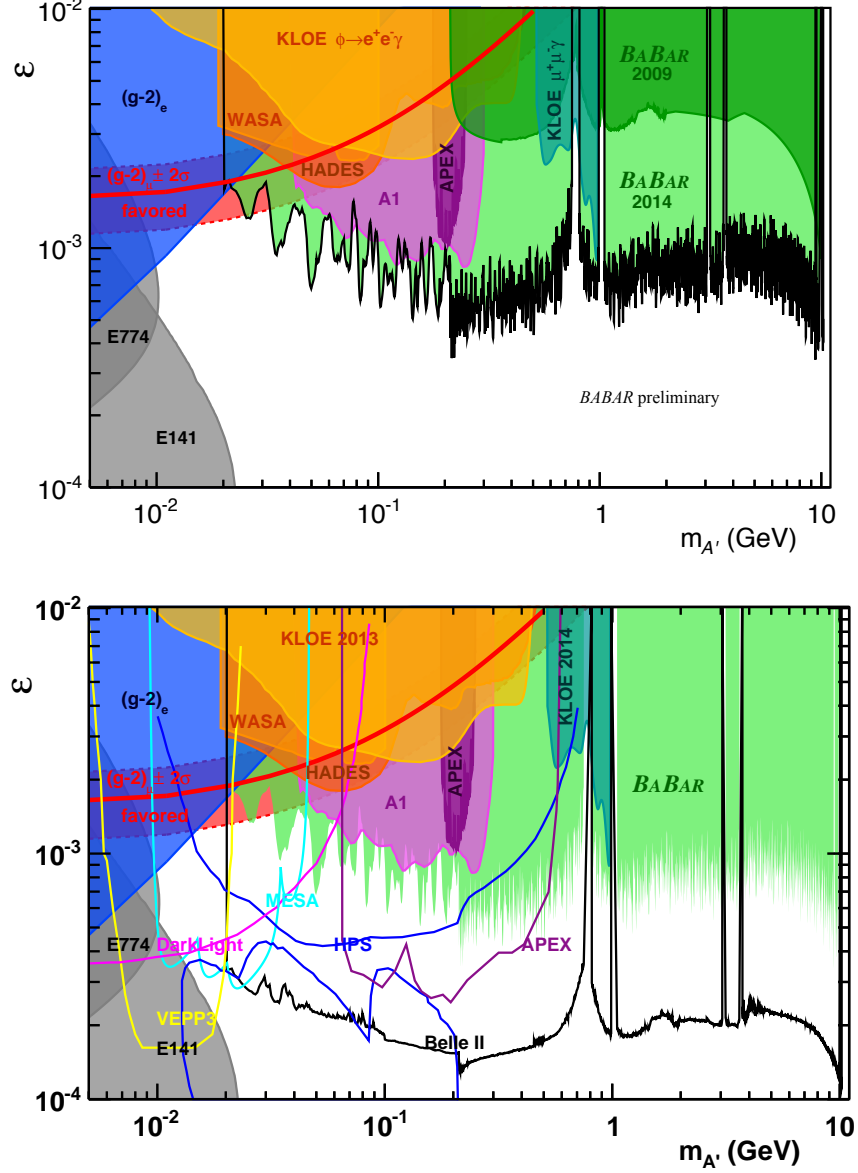


Figure 3: Top: Upper limits on the dark-photon mixing parameter ϵ vs. its mass $m_{A'}$ from various experiments. See text for details. Bottom: Current limits with projected sensitivities of future experiments.

4 Higgs-portal constraints

Although experiments have not searched directly for dark-Higgs states, they have studied processes with the same final-state topology, which can be used to set limits on dark-Higgs

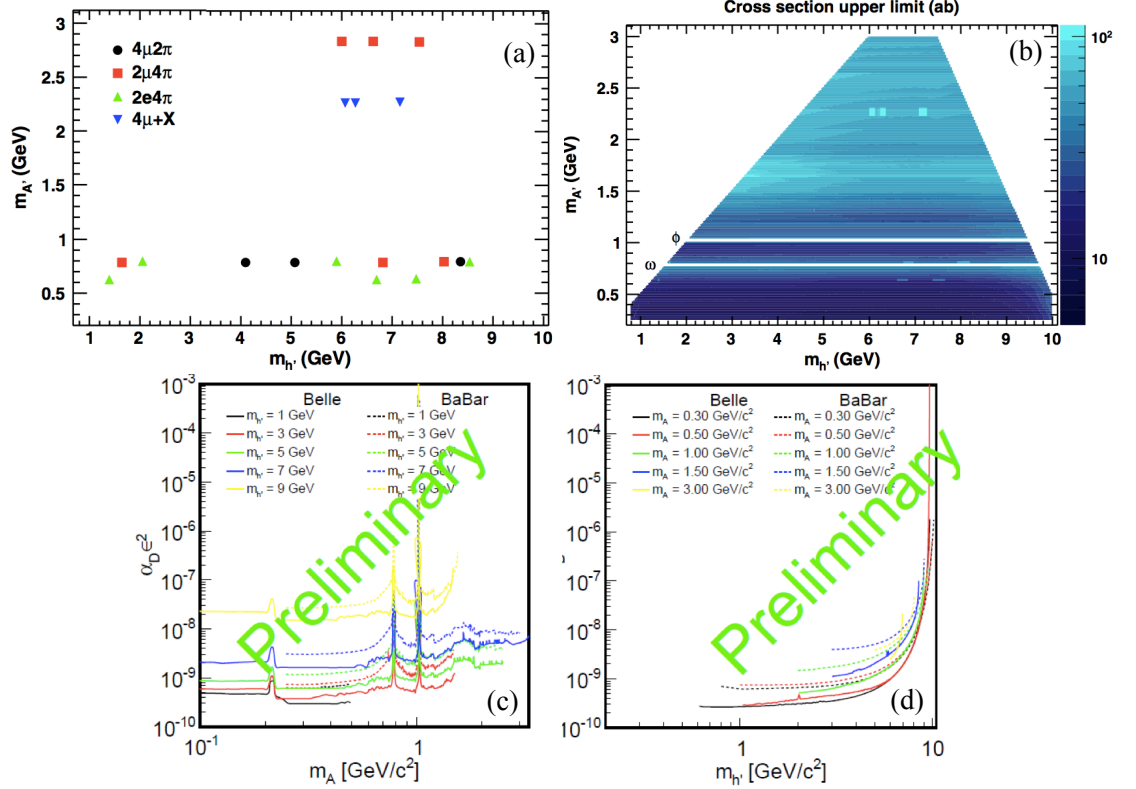


Figure 4: (a) The dark-photon mass $m_{A'}$ vs. dark-Higgs mass $m_{h'}$ for the three possible $h' \rightarrow A'A'$ assignments for each of the 6 events seen by *BABAR* [26] in the search for $e^+e^- \rightarrow A'A'A'$. (b) The resulting 90% CL limits on the production cross section. (c,d) The extracted limits on ϵ^2 times $\alpha_D = g_D^2/4\pi$, where g_D is the dark-sector gauge coupling, as a function of $m_{A'}$ and $m_{h'}$, from Belle [27] (solid lines) and *BABAR* [26] (dashed lines).

production.

4.1 Searches in Υ decays

BABAR has searched for the light, CP-odd Higgs A^0 of the NMSSM scenario [28, 29] using two methods. In the first method, one looks for production of A^0 in the radiative decay $\Upsilon(2S, 3S) \rightarrow A^0 \gamma$ (Fig. 1(b)), with subsequent A^0 decay into $\mu^+\mu^-$ [11], $\tau^+\tau^-$ [30], hadrons [31], or invisible particles [32]. This method has also been used by CLEO in radiative $\Upsilon(1S)$ decays, using a data sample of 1 fb⁻¹, with the A^0 final states $\mu^+\mu^-$ and e^+e^- [33]. The BES-III experiment has conducted a similar search in radiative J/ψ decays [34].

In the second method, the decay $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ is identified by reconstructing just the two pions and requiring the squared recoil mass $(p_{e^+e^-} - p_{\pi^+\pi^-})^2$ to be consistent

with production of an $\Upsilon(1S)$. This essentially eliminates the non- Υ background, so that despite the relatively small branching fraction $\mathcal{B}(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-) = 0.1785 \pm 0.0026$ [35], the two methods have comparable sensitivities. *BABAR* has used this method to search for $A^0 \rightarrow \mu^+\mu^-$ [36], $\tau^+\tau^-$ [37], hadrons [38], or invisible particles [39].

A summary of the results is shown in Fig. 5 for A^0 decays to leptons and invisible particles, and in Fig. 6 for decays to hadronic final states. The results are presented as limits on the relevant A^0 branching fraction times either $\mathcal{B}(\Upsilon(nS) \rightarrow A^0\gamma)$ or the squared couplings f_Υ and g_b , defined from

$$\frac{\mathcal{B}(\Upsilon(nS) \rightarrow \gamma A^0)}{\mathcal{B}(\Upsilon(nS) \rightarrow \ell^+\ell^-)} = \frac{f_\Upsilon^2}{2\pi\alpha} \left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right),$$

$$f_\Upsilon^2 = \sqrt{2}g_b^2 G_F m_b^2 F_{\text{QCD}}, \quad (3)$$

where F_{QCD} includes QCD and relativistic corrections of up to 30% to the $\Upsilon(nS)$ branching fractions.

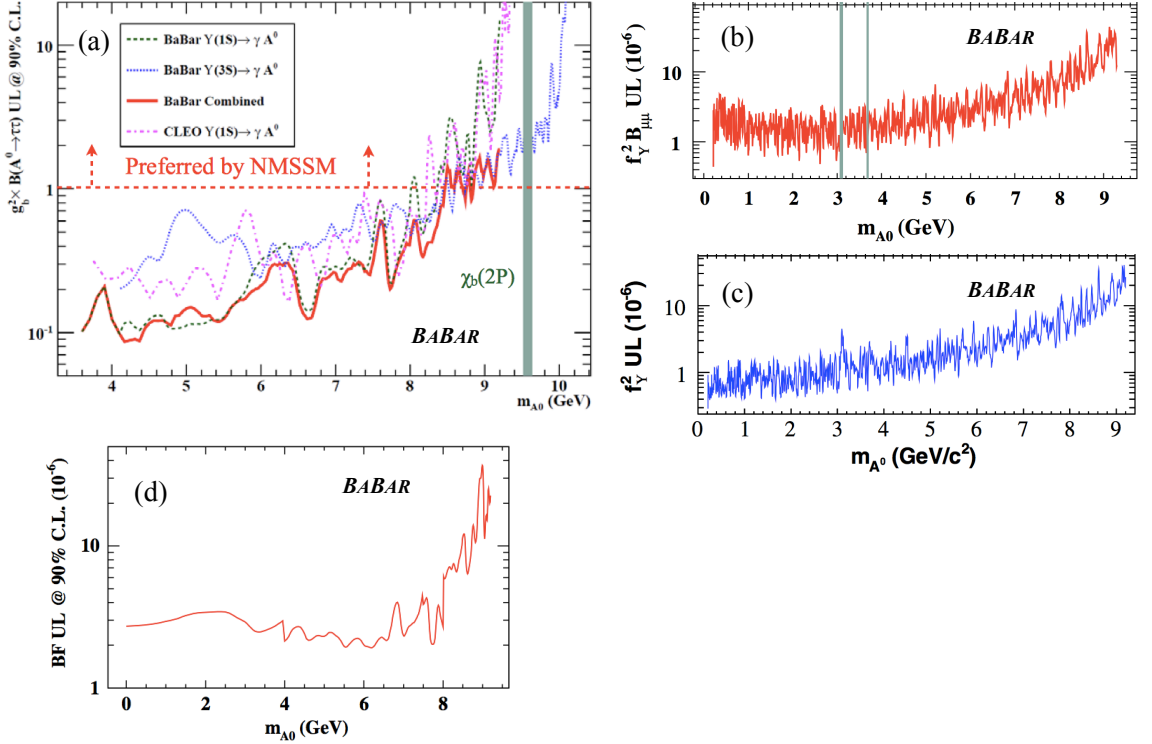


Figure 5: *BABAR* 90% CL upper limits, as functions of the light-Higgs mass m_{A^0} , on (a) $g_b^2 \mathcal{B}(A^0 \rightarrow \tau^+\tau^-)$ [30, 37] (limits from CLEO [33] are also shown), on $f_\Upsilon \mathcal{B}(A^0 \rightarrow \mu^+\mu^-)$ from (b) $\Upsilon(2S, 3S)$ decays [11] and (c) $\Upsilon(1S)$ decays [36], and (d) on $\mathcal{B}(\Upsilon(1S) \rightarrow A^0\gamma) \mathcal{B}(A^0 \rightarrow \text{invisible})$ [39]. (See Eq. (3) for the definitions of g_b and f_Υ .)

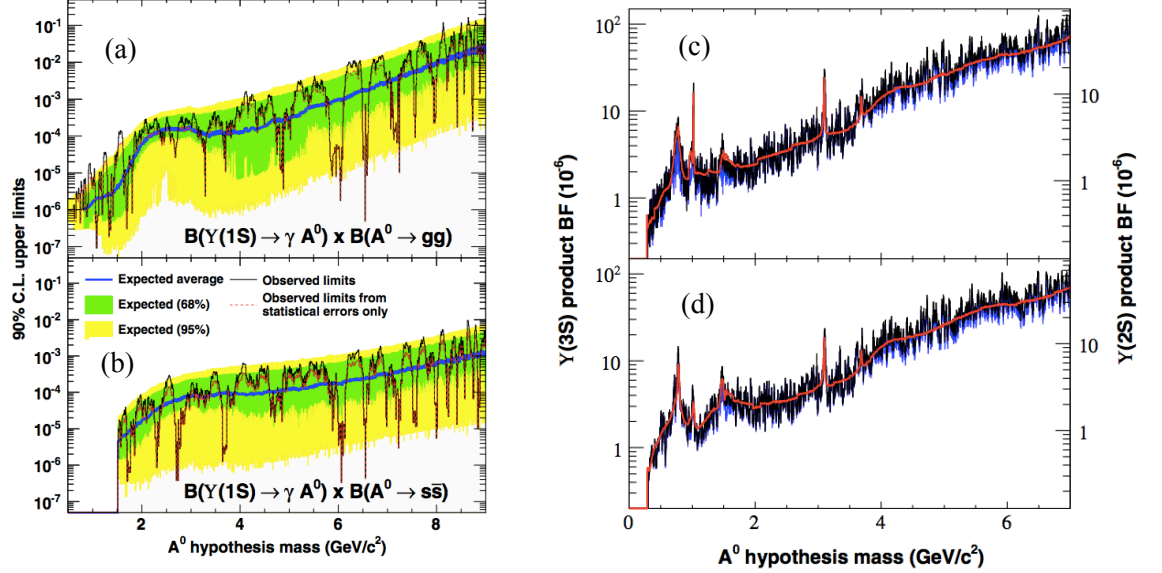


Figure 6: *BABAR* 90% CL upper limits, as functions of the light-Higgs mass m_{A^0} , on $\mathcal{B}(\Upsilon(nS) \rightarrow A^0 \gamma) \mathcal{B}(A^0 \rightarrow h)$ [31, 38], where the hadronic final state h is either (a) gg , (b) $s\bar{s}$, (c) all hadrons in the event, or (d) all hadrons in the event excluding the CP-even states K^+K^- and $\pi^+\pi^-$. The Υ states are (a,b) $n = 1$ or (c,d) $n = 3$ (left vertical axis) or $n = 2$ (right vertical axis, not including a phase-space correction of at most 3.5%).

4.2 Searches in penguin B decays

Limits on light-Higgs parameters have also been extracted from studies of electroweak penguin B decays (Fig. 1(c)). The dilepton invariant-mass-squared spectra for $B \rightarrow K^{(*)} \ell^+ \ell^-$ decays measured by CDF [40], Belle [41], *BABAR* [42], and LHCb [43] are shown in Fig. 7(a,b,c). Fig. 7(d) shows limits [4] on the coupling parameter y of Eq. (2), extracted from some of these results and from some of the Υ -decay results discussed in Sec. 4.1. We note that the LHCb result was obtained with a data sample of 1 fb^{-1} , only a third of the currently available sample. Analysis of LHCb's 50 fb^{-1} sample with improved triggers, expected during Run 2 of the LHC, will significantly improve these results. Older results on these decays by *BABAR* [44] and Belle [45] have been used to set limits on axion-portal parameters [46].

Limits on the branching fractions of $B \rightarrow K^{(*)} \phi$ with the scalar ϕ decaying into invisible WIMPS can be extracted from Belle [48] and *BABAR* [49, 50] searches for $B \rightarrow K \nu \bar{\nu}$, as well as a lower-luminosity search by CLEO [51]. As an example, we show in Fig. 8(a) the results for $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$ as a function of $s_B = m(\nu \bar{\nu})/m_B$. Fig. 8(b) shows limits [52] on the absolute value of the mixing parameter θ , defined using

$$\tan 2\theta = \frac{g_\theta \langle \phi \rangle \langle \phi_{\text{SM}} \rangle}{\lambda_{\text{SM}} \langle \phi_{\text{SM}} \rangle^2 - \lambda \langle \phi \rangle^2}, \quad (4)$$

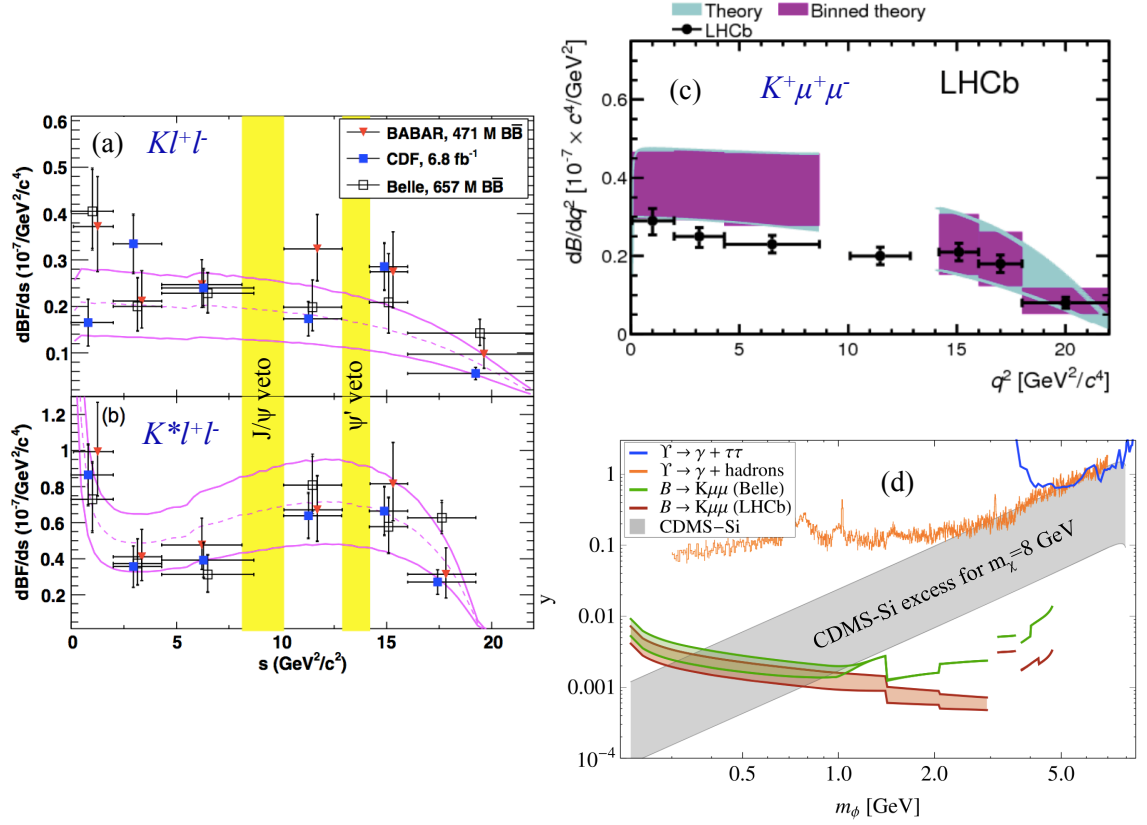


Figure 7: The $s = q^2 = m(\ell^+ \ell^-)$ spectra in $B \rightarrow K^{(*)} \ell^+ \ell^-$ measured by (a,b) CDF [40] Belle [41], BABAR [42], and (c) LHCb [43]. For CDF and LHCb, $\ell^+ \ell^- = \mu^+ \mu^-$ only, while Belle and BABAR results include also the $e^+ e^-$ mode. (d) Limits [4] on the coupling parameter y of Eq. (2) from some of these results (Belle and LHCb) in comparison to some of those from Υ decays (see Sec. 4.1) and to results from CDMS [47] (interpreted as signal), assuming a WIMP mass of $m_\chi = 8$ GeV.

where ϕ_{SM} is the SM Higgs field, λ_{SM} is the usual SM Higgs quartic coupling, and λ and g_θ are defined by the Lagrangian

$$\mathcal{L} = \partial_\mu \phi^\dagger \partial^\mu \phi + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 - g_\theta (\phi^\dagger \phi) (\phi_{\text{SM}}^\dagger \phi_{\text{SM}}) + \mathcal{L}_{\text{SM}}. \quad (5)$$

These $|\theta|$ limits are based on the limits on the total (as opposed to $m(\nu \bar{\nu})$ -dependent) branching fractions of the processes shown. Naively, the full Belle-II experiment will produce an order-of-magnitude improvement in the limits on $B \rightarrow K \chi \bar{\chi}$. Further improvement should come about by conducting a dedicated peak search rather than by using just the total branching fractions.

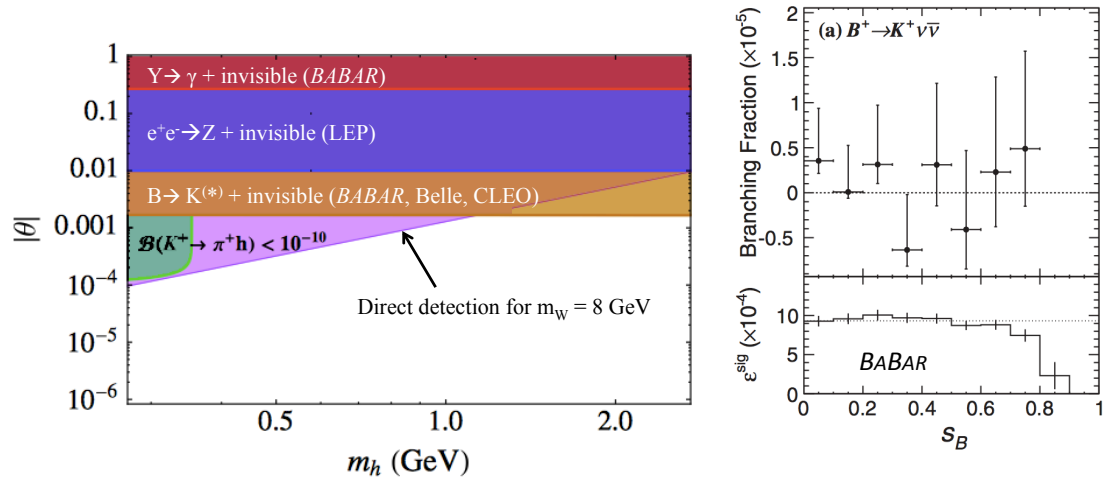


Figure 8: (a) Central values with uncertainties for the partial branching fraction of $B^+ \rightarrow K^+ \nu \bar{\nu}$ in bins of $s_B = m(\nu \bar{\nu})/m_B$ from BABAR [49]. The bottom plot shows the efficiency variation with s_B . (b) Limits [52] on the Higgs-mixing parameter θ of Eq. (4), based on the limits on the total branching fractions for $\Upsilon(1S) \rightarrow \gamma + \text{invisible}$ [39], $B \rightarrow K^{(*)} + \text{invisible}$ [48, 49, 50, 51], measurements of $\mathcal{B}(K^+ \rightarrow \pi^+ + \text{invisible})$ [53, 54], and limits on the cross section for $e^+e^- \rightarrow Z^0 + \text{invisible}$ at LEP [55, 56, 57, 58]. Also shown are the limits from direct-detection experiments, assuming a WIMP mass of $m_\chi = 8$ GeV.

5 Summary

Results from the B factories, fixed-target experiments, and flavor-physics measurements at hadron colliders have set tight limits on the parameter spaces of new-physics models involving low-mass bosons. We have presented limits on parameters of vectors and scalars that may couple to stable dark-matter particles, together comprising what has come to be called the dark sector. Constraints from current measurements are already ruling out significant regions of model-parameter space. Higher sensitivities will be achieved by the next generation of B -factory and fixed-target experiments, as well as from Run 2 of the LHC.

6 Acknowledgments

This research was supported in part by grant No. 2012017 from the United States-Israel Binational Science Foundation (BSF), and by grant No. 1787/11 from the Israel Science Foundation (ISF). I thank the IPA organizers, who put together an interesting and broad agenda and organized a well-run and enjoyable conference, as well as the conference partic-

ipants, whose excellent talks and subsequent conversations taught me a great deal.

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